Abstract—Over the past several years a joint cooperative effort between the DOC, DOD and NASA has been underway developing plans for this Nation's new generation of weather satellites known as the National Polar-Orbiting Operational Environmental Satellite System (NPOESS). One of the last groups of instruments being configured to support these missions is the Space Environment Sensor Suite (SESS). These instruments will measure space weather from multiple platforms over the next two decades. The subject of this paper is the complex trade that led to the "best value" selection of space weather sensors. The myriad of trade parameters that are considered, the significant cost constraints, and spacecraft accommodation limitations make this an interesting and educational trade study to consider and review.

The goal of the trade study and evaluation is to determine the best, most cost-effective, solution for SESS. This paper investigates how an industry contractor, Ball Aerospace & Technologies Corp., (BATC) as the SESS system integrator, under the direction of the prime contractor, Northrop Grumman Space Technology, and with guidance from many supporting sources, evaluated a wide range of instruments to determine the optimal solution for SESS.

Numerous technical performance comparisons were made. In addition, resource requirements, program risks, and system costs were all considered. Cost as an independent variable (CAIV) trades were performed at both instrument and integrated system levels. The desired system is a low-cost, low-development risk solution that provides the superior space weather measurements spanning the life of the program. The task was to perform in-depth analysis and show that the optimum solution was chosen. Because the evaluation was complex and involved, seemingly incomparable performance parameters needed to be related.

Sharing the results with the customer required:

1. Giving an unbiased perspective on the various suites that were considered
2. Sharing the data with experts possessing diverse backgrounds and interests
3. Utilizing feedback to iterate an improved solution
4. Being open to alternative heritage solutions

Thirteen important measurements of space weather were sought for the SESS system. These specific requirements are referred to as environmental data records or EDRs; 150 parameters that defined the EDRs were included in the trade space. Estimates of these parameters required substantiation by analysis, test, or heritage data. The work was accomplished utilizing all levels of the supplier chain, from prime contractor through component manufacturer. The role of the system integrator was to compile the vast data, integrate, analyze, and iterate for optimal solution.

A collection of instruments and data interpretation algorithms was conceived to meet EDR performance. Both the trade optimization methodology and solutions are presented in the paper.

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1. INTRODUCTION

The SESS system is a collection of instruments that will be used on the next generation NPOESS spacecraft to monitor space weather phenomena. It will gather information vital to global communications and power generation, as well as enhance the safety of astronauts and equipment operating in the space environment. Diverse measurements of the aurora, radio wave propagation, plasma density, and particle fluxes are made from the spacecraft, transmitted to the ground for processing, and made available to the diverse user community.

A number of space weather monitoring instruments have been developed and flown over the last forty years. Many of these have flown on short duration missions and were experimental in nature. The NPOESS platform provides an opportunity to fly refined operational versions of the best of these instruments simultaneously observing space weather phenomena on missions that will continue over the next two decades.

To develop the next generation constellation of space weather monitoring instruments, it is important to build on heritage designs and add benefits of new technologies. An extensive trade and evaluation process was conducted to define the best sensor suite of instruments.

Many partners were involved in the trade process to determine the best solution. These include the scientific community, government agencies, the spacecraft prime contractor, and instrument providers.

This paper describes the trade and evaluation process BATC used to converge on a “best value” solution for the SESS system. We evaluated many competing technologies, instruments, and configurations. These were presented to our customers and they in turn utilized this information to select the best space weather suite that will ultimately be deployed early in the next decade.

2. TRADE OBJECTIVES

The primary objective of the study was to develop a high performance, but affordable suite that satisfied spacecraft accommodations and system reliability requirements. At the heart of the trade studies were the conflicting requirements of cost and performance. Objective measurements of how well requirements were satisfied had to be made to compare the various solutions.

Biases in the study had to be identified, considered, and or calibrated out. Users had preferred requirements that they wanted met. These biases were balanced or prioritized so that the most important needs were considered first. Funding institutions had their experience base bias. It was important to provide information developed in the trades to validate or refute those biases. Manufactures, including BATC, had vested interests. These interests needed to be calibrated out of the studies. Our project role as system integrator always carried a higher priority than our company’s vested interests in instrument or sensors.

Other support issues also influenced the trades. As with any space mission, power and mass always significantly drive the system architecture. On the SESS selection, long life was also an important driver. The NPOESS satellites are designed to have a minimum service life of seven years.

3. METHODOLOGY

The process for performing the study is outlined in the following six steps:

1. Gather information
2. Analyze requirements
3. Develop trades at various levels
4. Evaluate performance and cost
5. Present results
6. Iterate on the preceding steps

These steps illustrate the general sequence in the trade study, but it should be noted that these activities also occurred somewhat concurrently and repetitively. The last step indicates that the entire process is iterative in order to converge on the best solution.

Gather Information

Information needed for developing the SESS architecture came from two fundamental sources:

1. The user community identified the needs in the form of requirements.
2. Manufacturers or supply side provided the list of capabilities

As would be expected, there are preferences, biases, and vested interests represented in data provided from both sources of information. The information sources are also overlapping in that users and providers are in many cases are represented by the same organization or institution.

Information was gathered from many sources. Requirements and clarifications came from the customer, primarily in three written documents. Basic guidance came from Technical Requirements Document (TRD), a General Instrument Interface Document (GIID), and a Government Advisory Team (GAT) System Requirements Review study report. NGST, the prime contractor gave considerable verbal and written guidance. Five specifications had a significantly effected the SESS suite. These specs were the: Mission Specification, General Instrument Interface Document, Environmental Requirements Spec., EMC Requirements Spec., and Design Practice Document. The data had been created by numerous space weather instrument experiments and data from previous POES and DMSP satellites. A large community of interested parties, including vendors, science users, and knowledgeable advisors provided information on various methods of collecting SESS data. Our own internal organization had a substantial database of instrument solutions as well.

The customer's TRD, identified the mission requirements in the form of 13 Environmental Data Records (EDRs). These requirements were broken into performance parameters at threshold and objective levels. **Figure 1** shows in decreasing importance each requirement. The NPOESS performance categorization of I, II and III and A and B indicates the relative need of each requirement to achieve threshold and objective performance levels. It also shows the customer's ranking for cost expenditure on the suite. As shown in Figure 1, the customer is interested in spending more to achieve objective performance of auroral boundary (IIA) than to measure energetic ions (IIB) at a threshold level. The fact that no SESS EDRs carry an IA ranking shows

IIA	**Auroral Boundary**
IIA	**Electron Density Profile**
IIA	**Electric Field**
IIA	**Geomagnetic Field**
IIB	**Auroral Energy Deposition**
IIB	**Neutral Density Profile**
IIB	**Medium Energy Charged Particles**
IIB	**Energetic Ions**
IIB	**Supra-Thermal to Auroral Energy Particles**
IIIB	**Auroral Imagery**
IIIB	**In-Situ Plasma Fluctuations**
IIIB	**In-Situ Plasma Temperature**
IIIB	**Ionospheric Scintillation**

Figure 1. Customer Prioritized EDRs for SESS

that they are cost sensitive and are especially interested in a “best value solution,” not only one that gives highest performance. This provided direction for the initiation of the study.

We identified a large variety of potential sensor solutions and requested information from industry, universities, and the science community on their solutions. Many instruments with significant space weather heritage were considered. Sensors with proven spaceflight experience were of primary interest because of the low risk, high-reliability needs of the NPOESS program. Less proven sensors in the development state were also of interest if they promised better compliance with requirements or other benefits. A substantial data collection and documentation process was part of the study process needed to uncover as many space weather instruments and analysis techniques as possible.

Analyze Requirements

Requirements analysis is simply a decomposition process. High level requirements are broken into more detailed requirements. The flowdown continues until specific measurable requirements are stated that can be assessed and quantified. The first level of requirements that flowed out of the thirteen EDRs were provided by the customer. The NPOESS SESS EDR requirements consist of approximately 150 performance attributes. Through these quantifiable attributes, the customer can judge the performance of the overall system. It was our responsibility to decompose the requirements further, in order to evaluate a particular instrument implementation. The attributes were partitioned into sets of requirements that could be addressed by different instruments, sensors, and detectors. Feasibility of achieving particular requirements was considered relative to available instrument solutions. To this, derived requirements were added that were peculiar to various hardware implementations.

Figure 2 shows the requirements flow-down process and the key outputs of each stage. The first stage “Requirements Analysis” is driven first by customer requirements and results in a strawman architecture. Because cost is a major driver in this and most system, Cost as an Independent Variable (CAIV) trades occur even in this initial process. The second stage of “System Architecture Optimization” involves much more analysis. Requirements decomposition and performance assessment of various system alternatives are used to develop a preferred architecture. CAIV trades drive this process to consider competing architectures. Design features

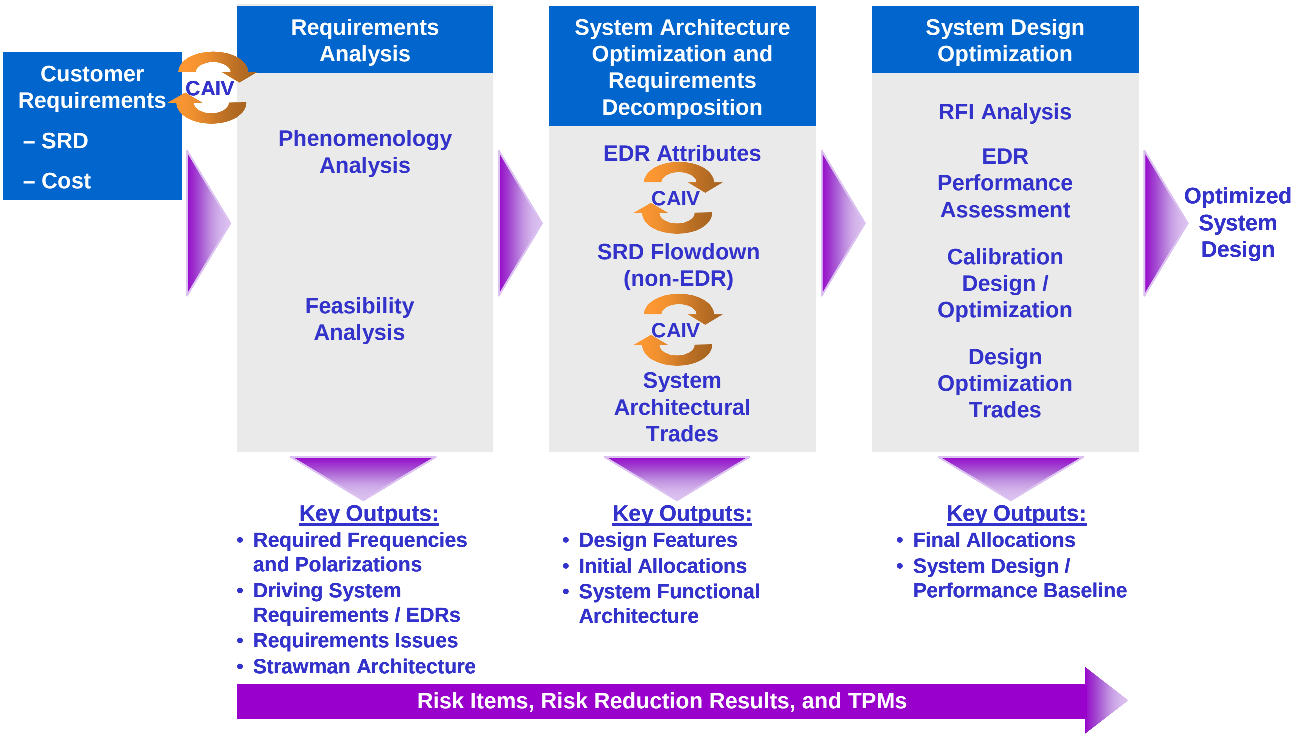


Figure 2. Requirements Flowdown and System Synthesis

result from the various configurations. The third stage "System Design Optimization" further refines the system. Together these stages provide a framework for accessing risk and defining Technical Performance Measures (TPMs).

As requirements were flowed down and instrument solutions developed, specifications were also created. Instrument requirements were created in parallel with instrument definitions. The requirements process for the SESS suite started as spreadsheet of performance tables and evolved to include detailed documents for each instrument. A suite designs matured, each instrument specification grew to require more than 200 pages to fully define their requirements. Central to these documents were the EDR performance parameters, but also significant were many other requirements that governed such things as: spacecraft accommodations, life requirements and reliability to insure that these instruments would successfully perform for this long-life mission. These documents were needed to fully define and control the instrument that various subcontractors would provide. Companies, universities, or laboratories specializing in unique space weather instrumentation will produce most SESS hardware. Hardware produced within our company was also driven to the same level of controlling documentation.

Develop Trades

Figure 3 shows competing solutions were identified at many levels of the SESS architecture. At the system level, various combinations of instruments were identified that could address the SESS solution meeting the balance of requirements. These were CAIV trades at the system or suite level. At the EDR level, competing instrument candidates were analyzed that addressed a single EDR. Finally, trades were considered at a component level that would influence the higher

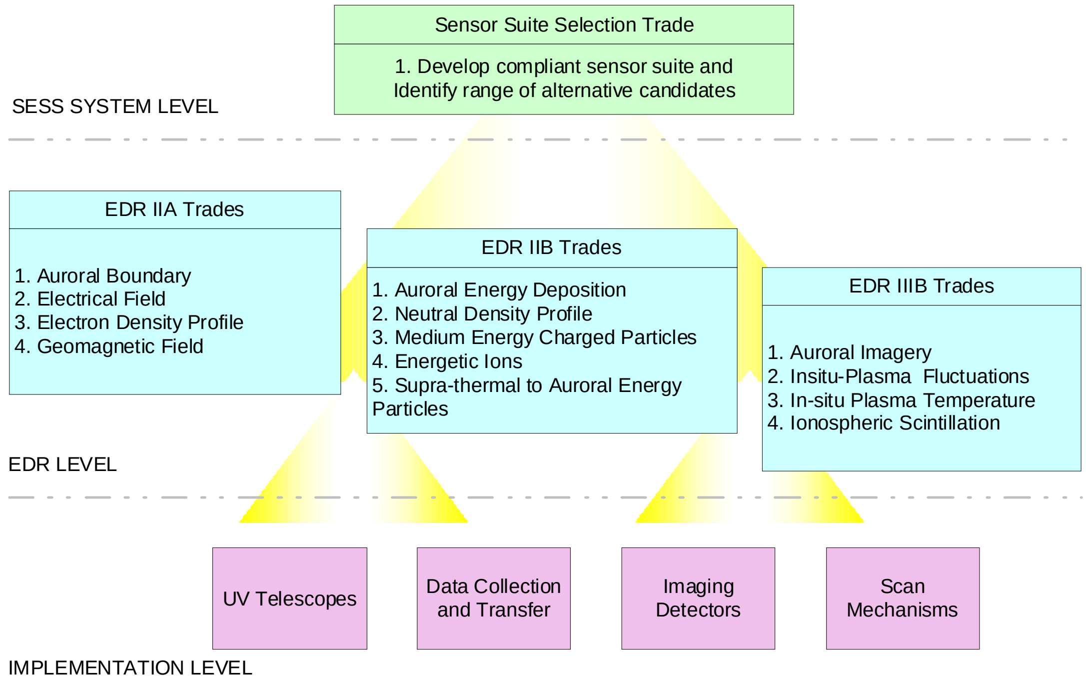


Figure 3. SESS Trades Considered at Various Levels

level trades. UV detectors, for example, strongly influenced system cost and required detailed evaluation. Trades at all levels drove the suite cost, performance, and risks. Increasingly lower levels were probed to find drivers that shaped the SESS system.

Evaluate Performance and Cost

Within the trade space, each of the alternatives could be compared to determine best value solutions. Performance analysis was made with cost as an independent variable (CAIV). Trades were made and vendor products were compared. In the initial stages, performance trades were comparisons of data from vendor queries, literature searches, and inputs from consultants. More detailed stages involved ROM costs. Cost analysis matured in parallel with the requirements development process. When specifications were completed cost proposals were requested. Each was evaluated in a fair and thorough manner using BATC Quality Business Systems methods. Technical evaluations were written on submitted competing proposals.

Presenting Results

As trades were completed, the results were documented and presented, first, to our dedicated project team and, then to a science review team that included recognized experts and finally to the customer. The data was compiled in a meaningful and clear manner. The results were as free from bias as possible. The information was shared; not only to show the best solution, but also to learn collectively what further trades might yield even better solutions. The goals of the presentations were to outline solutions such that the presenter and our audience could understand the implications of solutions and offer alternatives. The key was to make the information as easily understood as possible.

Figure 4 shows how trades were reported in a standardized trade table. This table shows how various magnetometer configurations were initially compared to one another. Coarse performance and cost comparisons were made even before requirements flowdowns and specifications were developed. The result of this initial magnetometer trade indicated that a longer boom was more cost effective than using higher precision mangetometers. In other cases the trades was inconclusive but the trade table documentation process allowed more visibility by various teammates and experts.

The interactive nature of some of the EDRs further complicated the trades. The electron density profile (EDP) required use of multiple instruments. UV instrumentation and RF instrumentation provided measurements of electrons and ion at various altitudes above and below the spacecraft. Charge particle sensors made direct measurements of the environment that the spacecraft was flying through. The approach that ultimately allowed simplification of many high level or suite trades was to satisfy the most important EDRs first. Then with those EDRs satisfied, the instruments were judged for their ability to satisfy the remaining requirements. In other words, a suite was first chosen that addressed IIA EDR needs. Second, it was evaluated on its ability to meet IIB and IIIB requirements.

EDR Geomagnetic II Threshold A Objective		Perform-ance require.		Cost	Sche	Risks			Algo.	Accom-modations				Limitations					
	Sensor ID	Threshold	Objective			Risk Factor	Mitigation	Probability		Volume	Mass	Power	Data rate	Reliability	Testability	Manufacture	Calibration	Growth/flexi	Simplicity
1 Complex mag				**$$**		**M**	**3**	**3**		**2**	**1**	**2**	**0**						
6 meter boom		E	B	$		1	L	L		1	1	1	0.1						
3 highly sensitive magnetometers				$$		1	L	L		1	1	1	0.2						
RAMs system																			
2 Standard mag																			
3 meter boom moderate sensitivity		M	B																
sensitivity																			
3 No mag																			
		B	B																

Does not meet all threshold requirements B — Hardware cost 7 systems + NRE — kbps
Potentially/arguably meets intended threshold require. M — $$$$$ 10M<x<30M — ^ — ^
Meets or exeeds all threshold requirements E — $$$$ 3M<x<10M — ^ Watts — .xx
$$$ 1M<x<3M — ^ Kilograms — ^
$$ 100K<x<1M — Liters
$ 10K<x<100K — ^ — High effort H
^ — ^ — D Develop — Manageable M
Does not address objective requirements B — Schedule na — A Adapt — Few problems L
Addresses some objective requirements M — ^ — ^ — O AdOpt
Meets significant objective requirements E — New data H — H >66% — Chance a major risk will reduce
Related HW M — M 33x<66 — performance below stated
Heritage data L — L <33% — threshold levels
^
H >50% $ to mitigate risk may exceed the $outlay
M 25<50 planned for the EDR
L <25% by this percent

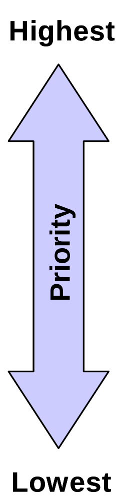
Figure 4. Typical Trade Table

Iterate

The process was repeated numerous times to converge on the best solution. Trades spawned new trades and information led to new analyses and methods. Trades were presented to others (work associates, an external science review team, management, and the customer) to select a balanced optimal configuration. Iterating and presenting designs at a variety of levels required a balance of methodical analysis with rapid cycle iterations. As more information was collected the analysis improved and greater details were developed. A maturation process was noted both in instrument and requirements definition.

Each of the above steps was essential to completing the trade study process. The iterative nature of synthesizing solutions to optimize the design was clearly a part of this complex trade study. Among the steps outlined above in the trade study, the *Evaluating Performance and Cost* process is the most revealing to consider further. Results of the evaluation were shared with our upper management and customer. In this process, our goal as system integrator was to help our customer find the best sensor solution.

Many of the iterations were completed by analysis within our organization. Others required feedback from the customer. **Figure 5** shows requirements were re-evaluated after our results were discussed with the customer. The bold text (in Red) shows additional requirements prioritization was provided after our results were shared with the customer. The changes generally did not reverse earlier customer priorities, it just added more details. As shown in the figure, spacecraft accommodations were integrated into the requirements prioritization table.



1. **Category IIA&B EDRs (Strive for threshold or better)**
2. **Cost**
3. **Category IIA&B EDRs 3-orbit coverage**
4. **Volume**
5. **Category IIIB EDRs (No $ to go beyond threshold)**
6. **Category IIIB EDRs 3-orbit coverage**
7. **Mass**
8. **Power**
9. **Data Rate**

Figure 5. Sensors Optimized for SESS

4. EVALUATION

The 13 prioritized EDRs showed the customer preference for SESS. The key trade metrics were to show satisfying highest priority EDRs first. In many cases, the group of instruments that satisfied these EDRs was able to contribute performance to a lesser or remaining EDR. The approach at the top system level began by providing the best CAIV solution and satisfying high-level EDRs. Comparisons were made using various instrument solutions. Electron Density Profile (EDP) was the highest priority system followed by Neutral Density Profile (NDP). The process became work on “what matters most” first, followed by lesser priority items. Addressing “what matters most” is done at all levels of the process. At the suite level we discovered that all SESS sensors were required just to achieve EDP threshold performance. With some enhancements the sensors provided or contributed to achieving the remaining 12 EDRs.

5. SHARING THE RESULTS

Figure 6 shows a detailed comparison of the trade study results. Thirteen EDRs are displayed along with the performance of 150 parameters. This comparison showed how one suite configuration performed. This graphing technique proved useful to summarize system performance to management and our customer. EDRs with below threshold performance were of particular interest. In presentations, these attributes were discussed in great detail. These below

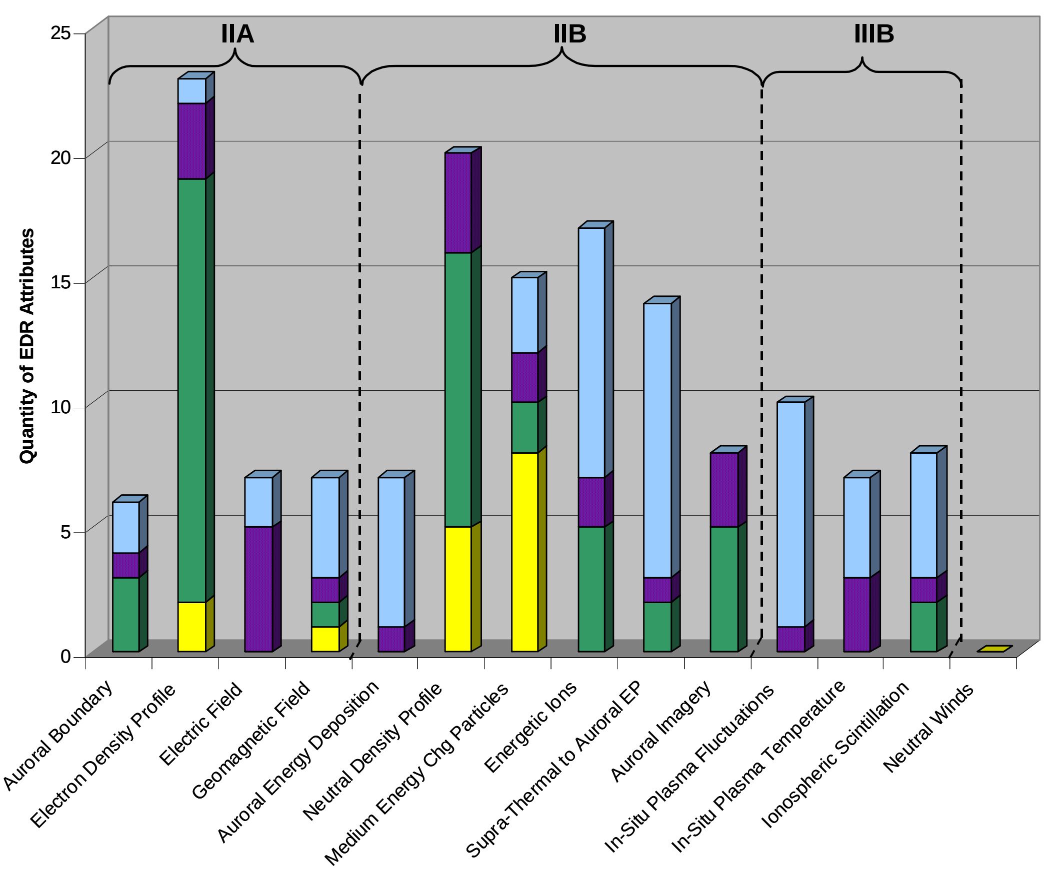


Figure 6. Suite Level Performance Comparison

threshold requirements were not necessarily bad conditions because of the prioritization it they were just a vital part of the CAIV analysis. In other words, was the cost of providing this performance worth the added cost?

As the system design matured the customer required more complex comparisons. This corresponded to the System Design Opimization stage described in Figure 2. **Figure 7** shows a summary trade that compared multiple sensor combinations distributed on three orbit planes. Performance was compared and price comparisons were made. This gave the customer a top level comparison of many different system configurations.

The SESS system architecture resulting from these trades is shown in **Figure 8**, These sensors are required to provide the space weather system that will fly on the NPOESS spacecraft. Some sensors like the Disk sensor will be installed on each of six satellites others will fly on as few as two.

The complex trade analysis was conducted at the start of the program in order to develop a most cost effective solution for SESS. The work was a collaborative effort by numerous teams that worked together to systematically come up with an initial baseline from which to start preliminary design. That effort is now underway.

Figure 7. Detailed Multi-Orbit Suite Comparison

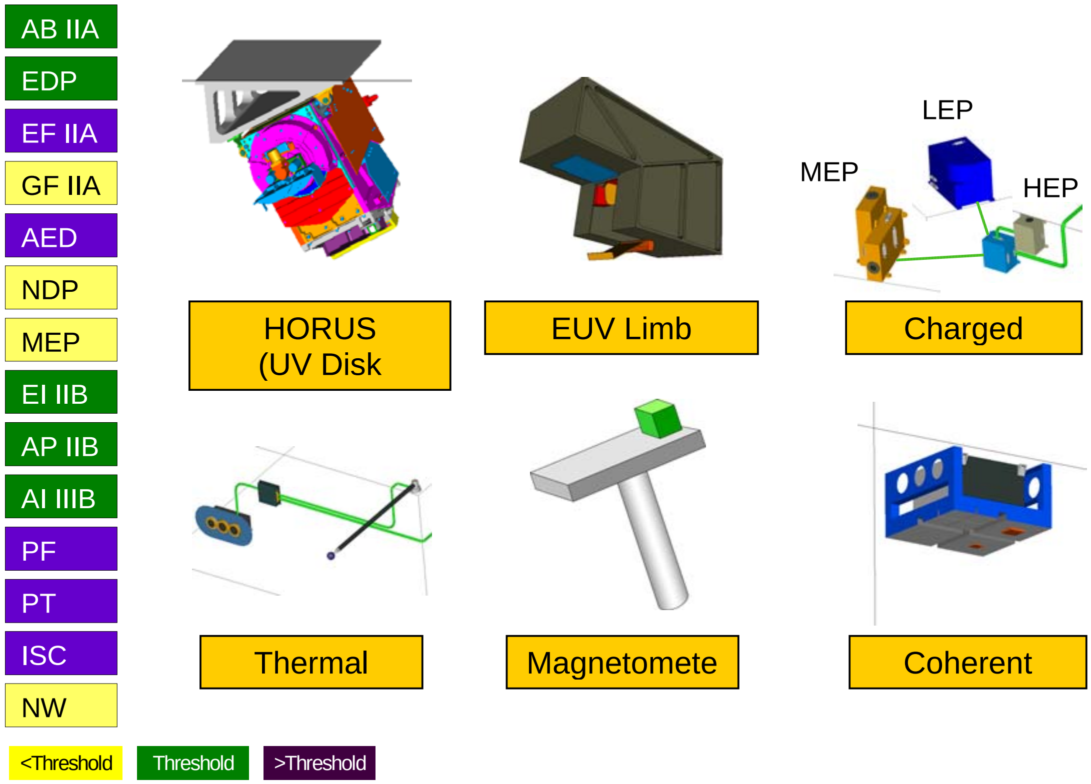


Figure 8. SESS Instrument Selection

6. CONCLUSION

A complex trade study was conducted to determine the optimal solution for SESS. It allowed all participants visibility into the process and to guide the solution from detailed designers up through management and on into the customer's organization. The process, though only loosely defined by the requesting agency, allowed convergence on a "best-value" solution while expending minimal resources.